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A continental scale analysis of threats to orchids

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ABSTRACT

Thousands of plants are at risk of extinction globally due to human activities, including many species of orchids. In Australia alone there are 184 orchids identified as threatened by the Australian Government, but what threatens them and where are they threatened? Using data derived from listing documents for these orchids, threats were allocated to 28 categories. Then, the distributions of the orchids and hence likely geographic patterns of threats were mapped using 14,651 location records from the Atlas of Living Australia. The most common threats were changes in fire regimes (74% of threatened Australian orchids), invasive species (65%), habitat modification (64%), grazing (63%), tourism and recreation (47%) and illegal collection (46%), which often co-occurred as threat syndromes. Most threatened orchids are terrestrial (165 species), and many occur in temperate forests (96) and temperate shrubland (36). When generalised linear models were used to assess geographic patterns in threats, bioregions with less cover of native vegetation were more likely to have orchids threatened by habitat modification, grazing or weeds ($p < 0.05$). Bioregions with higher protected area coverage were more likely to contain orchids threatened by tourism and recreation, but less likely to have orchids threatened by habitat modification ($p < 0.05$). Understanding drivers of threats and their distribution is crucial for successful management as they highlight key areas for conservation. The results also highlight the need for updating orchid listings nationally and internationally to better reflect the diversity of orchids threatened and threats to them, including the increasing impact of climate change.

1. Introduction

The risk of species extinction is rapidly increasing globally due to human activities and impacts and is now several orders of magnitude greater than in the past (Pimm and Raven, 2000; Evans et al., 2011). Currently there are around 12,500 species of plants listed as threatened with extinction on the International Union for the Conservation of Nature (IUCN) Red List and it is predicted that 7–14% of vascular plant diversity will be lost by 2050 (van Vuuren et al., 2006; IUCN, 2016a). When attempting to ameliorate threats to plants it is important to establish what is threatening which species and where.

It is well recognised that habitat loss is a driving factor for many plant extinctions (Helm et al., 2006; Brook et al., 2008) with the scale and speed of habitat loss reflected in measures such as the global 7.7% decline in tree cover since 2010 (Global Forest Watch, 2014). Other common threats to plants include introduced species, inappropriate fire regimes, pollution and overexploitation (Venter et al., 2006; Burgman et al., 2007; Evans et al., 2011). Standardised datasets such as the IUCN Red List have been used to assess large scale patterns of threatened species and threatening processes (Schatz, 2009; Bilz et al., 2011; Ballantyne and Pickering, 2013; Brummitt et al., 2015; Kull et al., 2016; Wraith and Pickering, 2017, 2018). These datasets provide a valuable resource for understanding where threatened species occur and what threatens them, while recognising their limitations including that they often do not fully reflect the distributions of threats (Joppa et al., 2016). Understanding these threat distributions is important as it allows management and conservation efforts to target areas with co-occurring threats such as habitat loss, fire and weeds (Brooks et al., 2006; Evans et al., 2011; Baral et al., 2014) including at a continental and country level.

Australia is a large (7.7 million km^2) and geographically isolated continent with a diverse climate, soils and topography resulting in 89 bioregions containing different types of vegetation. Reflecting this diversity in habitats is high biodiversity, with ~24,700 species of native plants, ~86% of which are endemic to the continent (Australian Government, 2015). Because of increasing human activities over the last 200 years, biodiversity has declined dramatically (Steffen et al., 2009; Australian Government, 2011; Baral et al., 2014) with 1289 plants listed as threatened with extinction by the Australian Government (Australian Government, 2016a). The most common threats to plants in Australia are similar to those globally, and include habitat loss, introduced species and inappropriate fire regimes (Burgman et al.,

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Table 1
Details of the 28 threat categories used to code data from the Australian Government listings for threatened orchids used in the analysis.

Threat category	Definition of category
Animal digging	Animals digging up orchid tubers such as rabbits and pigs
Change in fire regimes	Inappropriate increase or decrease in natural fire intensity or frequency
Change in hydrology	A change in the natural hydrology of an area
Change in salinity	A change in the natural salinity levels due to human activities such as agriculture and development
Climate change	A significant change in the natural temperature and/or precipitation
Drought	Reduced precipitation causing drier than normal conditions
Edge effects	Damage to the boundary of multiple habitats
Erosion	Increased erosion due to human activities such as land clearing
Flood	Inundation of the area either naturally or enhanced by human activities
Forestry	Practices within forestry or development of new forestry such as logging
Grazing	Includes grazing of orchid flower or stem by agricultural species such as cattle or invasive species such as rabbits and pigs
Habitat modification	A loss of habitat from land clearing and habitat fragmentation
Hybridization	An increase in genetic hybridization reducing genetic diversity
Illegal collection and flower picking	The removal of entire orchid plant from the wild or removal of flower
Insect damage	Damage from insects eating orchid plants
Loss or decline of pollinator	The decline of key pollinators
Mining/quarry	The activities or development of mines and quarries
Pathogens	Pathogens such as *Phytophthora cinnamomi*
Pollution	Chemical pollution such as agriculture run-off
Residential and industrial development	Reducing suitable habitat for orchid populations or directly removing populations
Roads and road maintenance	Slashing on road side and the development/widening of roads
Rubbish dumping	Causing direct crushing of populations or long-term habitat destruction
Small population size	An at-risk population which is too small to maintain genetic diversity
Stochastic fire and weather events	Natural but extreme weather and fire events
Tourism and recreation	Recreation activities and trampling from tourists and enthusiasts either by foot, 4WD, bikes, horses and camping, the development of tourism infrastructure
Track maintenance	Maintaining tracks in protected areas for visitor use or management practices
Vehicle damage	Direct damage from public, construction or management vehicles
Weeds	Invasive vegetation

2007; Raven and Yeates, 2007; Evans et al., 2011; Australian Government, 2011). Previous spatial analysis in Australia has highlighted threat distributions across the continent at a broad scale for plants and animals (Evans et al., 2011), but little is known for specific plant groups such as orchids.

Orchids are the most diverse group of flowering plants globally, with over 26,567 species occurring in a wide range of bioregions (Cribb et al., 2003; Jones, 2006; Swarts and Dixon, 2009a; Li et al., 2018; Fay, 2018). Although there are a wide diversity of orchids occurring in many countries, most species are rare due to small population sizes, species specific symbionts and niche habitats resulting in limited distributions (Swarts and Dixon, 2009a). As a result, they are particularly at risk from a range of anthropogenic threats with Orchidaceae the most threatened group of flowering plants worldwide (Swarts and Dixon, 2009a; Zhang et al., 2015). Australia contains many orchids, with approximately 1794 species, of which 184 (10%) are threatened with extinction (Australian Government, 2016b).

The removal of native vegetation via land clearing (and the resulting fragmentation) for residential and commercial development, agriculture, roads and forestry has a severe impact on orchid populations globally (Vogt-Schilb et al., 2015; Wraith and Pickering, 2017, 2018; Fay, 2018). Orchids in the wild also experience high levels of illegal collecting and increasingly are the focus of specialist nature-based tourism, particularly in some protected areas (Ballantyne and Pickering, 2013; Subedi et al., 2013; Ghorbani et al., 2014; Rankin et al., 2015; Phelps and Webb, 2015; Hinsley et al., 2017; Wraith and Pickering, 2017, 2018). Previous studies on threatened orchids globally have shown that these threats, among others such as climate change and pollution, can co-occur and act as threat syndromes (Zotz and Schmidt, 2006; Bilz et al., 2011; Vogt-Schilb et al., 2015; Wraith and Pickering, 2017, 2018). But what are the threats to Australian orchids, where are there threatened orchids, and what is the continental distribution of these threats?

The aims of this study are to determine: (1) How many and what types of orchids are threatened in Australia? (2) Where are there threatened orchids? (3) What threatens orchids and do threats co-occur as threat syndromes? (4) What is the distribution of threats to orchids? and (5) What factors may account for the geographical patterns found in threatened orchids and in threats to orchids across the continent? The results of this analysis will highlight conservation and management priorities for threatened orchids in Australia.

2. Methods

2.1. Data collection

To assess geographical patterns in threatened orchids and their threatening processes, data was collected from the Species Profile and Threats Database collated by the Australian Government, which lists all species threatened under the *Environment Protection and Biodiversity Conservation Act 1999* (Australian Government, 2016b). Species, including orchids, listed under this Act are protected and managed with legal protection status in Australia. These listings were analysed to find information on each of the 184 threatened orchids including their scientific and common name, conservation status, habitat, growth form (e.g. if it is epiphytic, lithophytic or and terrestrial), which state or territories it occurs in, and threats (Jones, 2006; Australian Government, 2016b). Subfamilies of each genera were determined using recent phylogenetic research (Chase et al., 2015). The different sources of information were then entered into a specific database for the study. To be able to analyse and compare threats, detailed information in the listing documents for all listed species was assessed and then used to categorise the threats into 28 categories. The threat categories we developed and used here were similar to those used in the IUCN Red List threat categories but were designed to also reflect the types of threats and details about threats available for Australian orchids (Table 1). For species habitat types, the information from the listings was used to allocate species to habitat categories using the IUCN habitat categories (IUCN, 2016b). The IUCN Red list itself could not be directly used in the analysis as there are only five threatened orchids in Australia currently included on the Red List (IUCN, 2016a). Differences between endemic and none endemic species could not be assessed

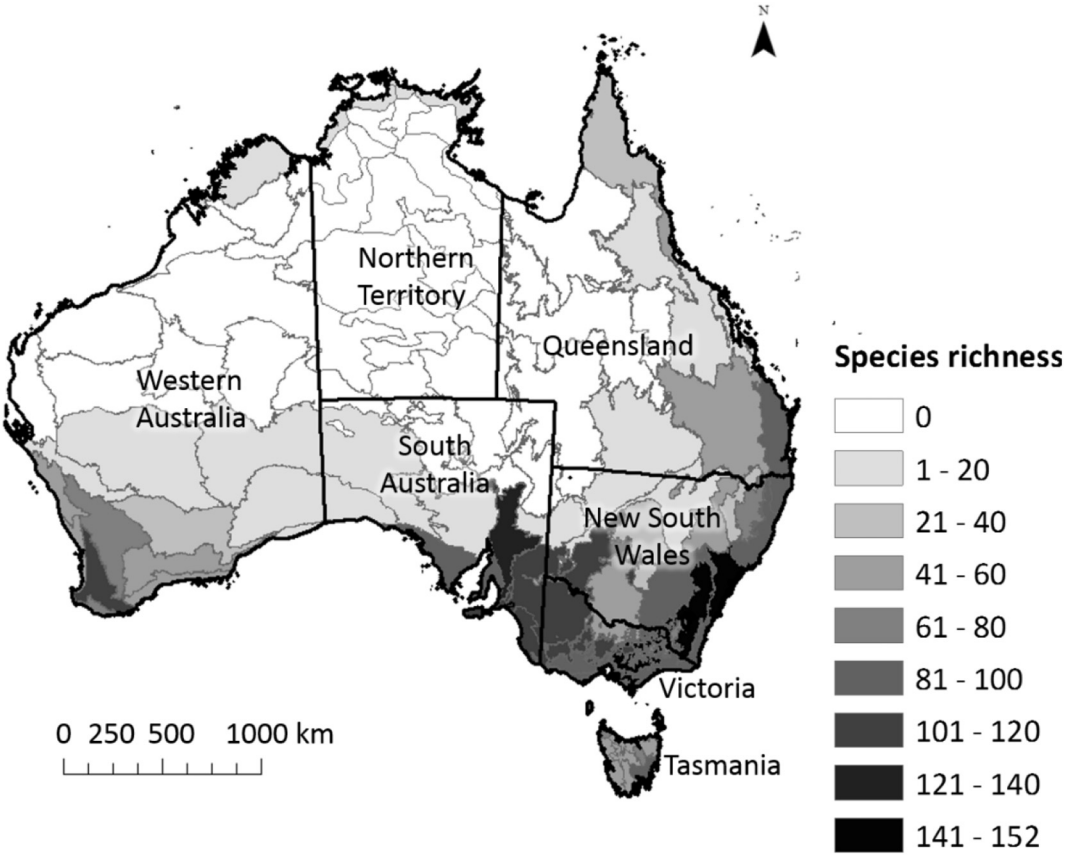

Fig. 1. Species richness of the 805 species orchids with adequate location data in the Atlas of Living Australia in relation to the 89 bioregions and the Australian states and territories.

currently, because at a broad scale (Australia) nearly all (96%) of species are endemic, and at regional and local scales, adequate accurate location data was not publicly available.

To assess where threatened orchids occur and patterns in threats across the continent, location data from the Atlas of Living Australia were used. The Atlas of Living Australia contains over 82,000,000 records for approximately 124,000 species of all flora and fauna in Australia and is collaboratively collected and compiled by scientists, conservation groups and institutions such as herbariums (Atlas of Living Australia, 2018). Data on the distribution of all orchids in Australia, including threatened orchids, were obtained from the Atlas of Living Australia database in January 2018, with 132,945 location records obtained for 1461 of the 1794 orchid species in Australia (Atlas of Living Australia, 2018). These data were screened for inaccuracies in spatial locations including locations outside the Australia's boundaries or missing location coordinates, unidentified or incorrect species, misspelled species names and formatting errors. After screening there were 87,222 location records for 805 species of orchids suitable for further analysis including 14,651 location records for 179 of the threatened orchids.

2.2. Data analysis

An initial analysis was conducted to assess how many and what types of orchids are threatened in Australia and identify patterns in the data. To do this, the number of orchids by growth form, habitat type and government jurisdiction (states and territories) was calculated for critically endangered, endangered and vulnerable orchids. To determine whether there were significant differences in conservation status (critically endangered, endangered or vulnerable) depending on which subfamily the species falls within (Orchidoideae or Epidendroideae), a Chi-squared analysis was performed using the statistical program RStudio (RStudio Team, 2016). It was important to assess patterns in threatened orchids for specific states and territories in Australia as most on ground management of threatened species is administered via the six states and two territories. Although states and territories maintain their own lists of threatened orchids associated with state or territory legislation, these more localised lists were not appropriate to use at the continental scale, as a species may be considered threatened within a specific state or territory, even though it is not threatened at the broader continental scale.

More detailed data on the distribution of threatened orchids across the continent (179 species) was then assessed in ArcGIS 10.4.1 using the location data obtained from the Atlas of Living Australia (ESRI, 2016). To compensate for imprecise and/or limited data per species, convex hull polygons were generated around all location points for each threatened species. These polygons encompass all occurrence points for each threatened species at its smallest geographic envelope. The polygons were then treated as hypothetical boundaries of occurrences. Due to the inexact nature of much of the location data, which are often intentionally left vague to avoid illegal collecting, detailed analysis using species distribution models could not be conducted.

To determine the most common threats to orchids within each state and/or territory, the number of orchids per government jurisdiction was calculated for each threat. To determine if there were threats that co-occurred including habitats, a Resemblance analysis (S17 Bray Curtis Similarity) was used (for threats and habitats with > 20 threatened species) in the ordination package PRIMER (Clarke and Gorley, 2006). This method was used to identify clusters of species with high levels of similarity in threats and habitat types.

Interpolation analysis was used to visually assess the distributions of the six most common threats using ArcGIS 10.4.1 (ESRI, 2016). This

involved converting the overlapping polygon counts to point format and then conducting an interpolation on these data. A spline with barriers was chosen to visualise areas with many threatened species, as the technique smooths all given point values (Mitas and Mitasova, 1999; Benito Garzón et al., 2007). The interpolation was repeated for the six most common threats, acting as a surrogate for the distribution of threatening processes.

To assess the drivers of threat distributions, the percent of threatened species richness (based on the 179 species) was compared to total orchid species richness (based on the 805 species) for the six most common threats per bioregion within Australia. Bioregions (Australian Government, 2012) are a well-recognised categorisation system for assessing land use, biodiversity, geography, topography and climate in Australia and are used for a range of vegetation studies at a continent scale (Hutchinson et al., 2005) with 60 of the 89 bioregions in Australia containing orchid species (Fig. 1). Species richness for each bioregion was calculated using polygon counts and the identity tool in ArcGIS 10.4.1 (ESRI, 2016). The relationship between the total species richness and the total number of threatened species per bioregion was visualised using a scatterplot.

Additional GIS layers were then used to identify factors associated with the distribution of threats. This included factors such as the availability of natural habitat for orchids (e.g. percentage cover of native vegetation per bioregion) (Geoscience Australia, 2006), how much area is protected for conservation (e.g. the percentage cover of protected areas per bioregion) (Geoscience Australia, 2006), how much of the bioregion has been converted to built areas (percentage of built areas per bioreigon) (Geoscience Australia, 2006) and the climate of the bioregion (e.g. whether the bioregion was predominantly a temperate or arid Koppen climate zone) (Kriticos et al., 2012). These layers were treated as independent variables and values for each variable per bioregion were calculated using the identity tool in ArcGIS 10.4.1 (ESRI, 2016).

Generalised linear models (GLM) were then used to determine if these 'independent' variables predict the percentage of threatened species overall, and then for each of the six most common threats per bioregion (Table 2). Generalised Linear Models with a Quasi-Poisson log link distribution were used due to over dispersion and a deviance higher than the degrees of freedom in R studio (RStudio Team, 2016). Only bioregions with an overall species richness of 20 or more species (e.g. 40 bioregions) were used in the models.

3. Results

3.1. How many and what types of orchids are threatened in Australia?

There were 184 orchid species listed as threatened by the Australian Government in 2018 (Table A1), of which 44 are critically endangered, 96 endangered and 46 vulnerable (Fig. 2). Most are terrestrial orchids (165 species) of which 26% are critically endangered, 52% endangered and 22% vulnerable (Fig. 2). There were only 15 threatened epiphytic species, most of which are terrestrial or epiphytic and included one

Table 2
Independent and dependent variables used in generalised linear models assessing the importance of the variables in accounting for geographic patterns in threatened orchids across 40 bioregions in Australia.

Independent variables (per bioregion)	Dependent variables (per bioregion)
% native vegetation cover	% threatened species
% protected area cover	% species threatened by habitat
% built area	% species threatened by grazing
Koppen climate (temperate or arid)	% species threatened by weeds
	% species threatened by tourism
	% species threatened by fire
	% species threatened by collection

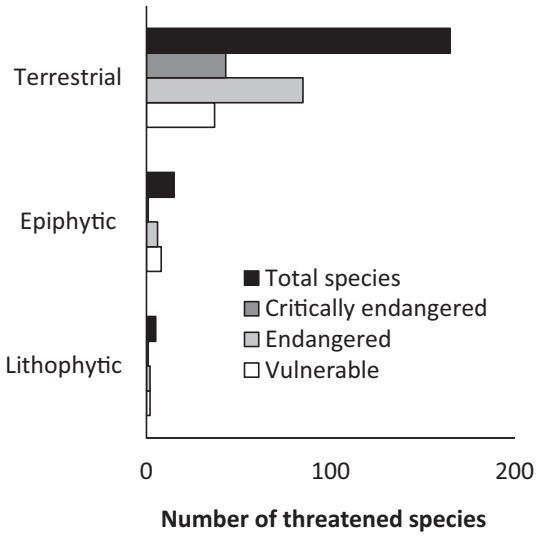

Fig. 2. The number of species by growth form and their corresponding threat status for 184 threatened orchids in Australia.

critically endangered, six endangered and eight vulnerable species. Of the five lithophytic (plants which grow on rocks) orchids listed, one is critically endangered (*Oberonia attenuata*), two are endangered (*Dendrobium lithocola* and *Phalaenopsis rosenstromii*) and two are vulnerable (*Sarcochilus fitzgeraldii* and *Sarcochilus hartmannii*). There were 34 genera of orchids threatened, with 16 genera having only one threatened species. There were, however, some genera with several species threatened including *Caladenia* (61 species listed), *Prasophyllum* (38), *Thelymitra* (11), *Pterostylis* (10), *Diuris* (8) and *Genoplesium* (8). Of the 184 threatened orchid species 88% were classified in the Orchidoideae subfamily and the remainder fall under Epidendroideae in which the proportion of conservation status (critically endangered, endangered and vulnerable) varied significantly among the subfamilies (Chi-squared test, $p < 0.001$).

Threatened orchids are found in nine habitats but were most common in temperate forests (96 species), temperate shrubland (36 species) and Mediterranean-type shrubby vegetation (25 species) (Fig. 3). In contrast, there were very few threatened orchids in rocky areas, seasonal or internment wetlands or subtropical/tropical dry

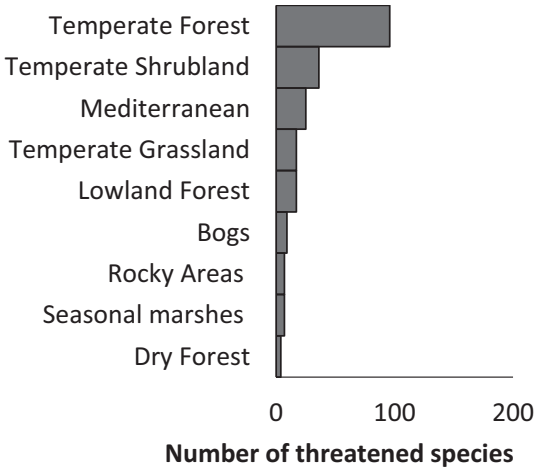

Fig. 3. The number of species per habitat type for 184 threatened orchids in Australia, where Dry Forest refers to (subtropical/tropical dry forest), seasonal marshes (seasonal/intermittent freshwater marshes/pools), bogs (bogs, marshes, swamps, fens, peatlands), lowland forest (subtropical/tropical moist lowland forest) and Mediterranean (Mediterranean-type shrubby vegetation).

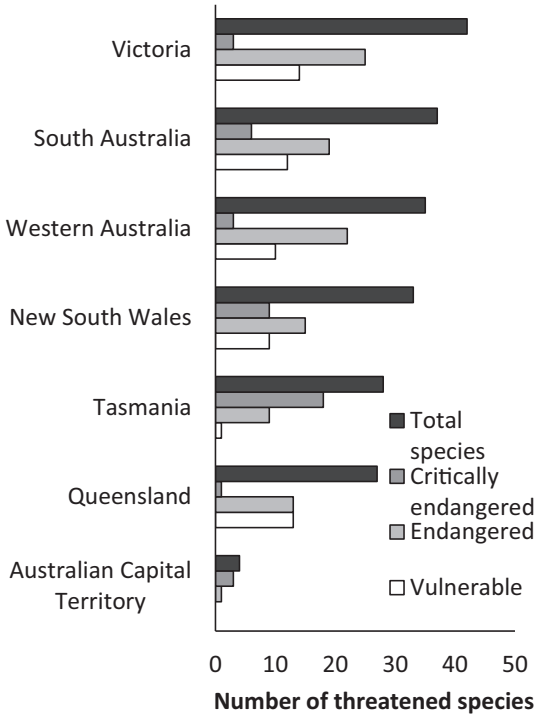

Fig. 4. The number of threatened orchid species listed within each Australian state or territory and their corresponding threatened species status.

forest areas in Australia.

3.2. Where are there threatened orchids in Australia?

Among the different government jurisdictions within Australia, threatened orchids were recorded in all states and territories except the Northern Territory (Fig. 4). Many threatened orchids occur in Victoria with 42 species listed, of which 7% are critically endangered, 60% endangered and 33% vulnerable. South Australia has 37 threatened species, of which 16% are critically endangered, 51% endangered and 32% vulnerable. Although there is a great diversity of orchids in Western Australia (Fig. 1), there are only 35 species listed as threatened, of which 9% are critically endangered, 63% are endangered and 29% are vulnerable. In New South Wales there are 33 species of threatened orchids of which 27% are critically endangered, 45% are endangered and 27% vulnerable. Tasmania (28 species) had the highest proportion of orchids imminently at risk of extinction with 64% of those threatened in the state, listed as critically endangered (Fig. 3).

When the distributions of threatened orchid species in Australia were analysed using location data from the Atlas of Living Australia (Fig. 5), finer scale spatial patterns were more apparent than when using the numbers per state or territory. For Western Australia, nearly all the threatened orchids are found in the south west of the state, an area with a Mediterranean climate that is internationally recognised for its mega-biodiversity. In contrast, there are few threatened orchids in the hot dry north of the Western Australia, or in the Northern Territory. In Queensland, there many threatened orchids in the north eastern tropical coast including in the World Heritage listed Wet Tropics, another area of mega-biodiversity. The largest concentration of threatened orchids in Australia, however, was not in areas of mega-biodiversity, but in the temperate areas of south eastern Australia including much of Victoria and Tasmania and the coastal parts of New South Wales, which include some areas high in terrestrial orchid diversity (Fig. 1 vs Fig. 5). Some areas of South Australia, including the south east of the state had high species richness of orchids (Fig. 1), but few of them are currently listed as threatened by the Australian Government (Fig. 5).

3.3. What threatens orchids in Australia and are there threat syndromes?

There are a wide range of threats to orchids in Australia. The most common is changes in fire regimes, putting 74% of all threatened Australian orchids at risk of extinction, particularly orchids in Victoria and Western Australia (Fig. 6). Invasive species, such as weeds, are the second most common threat (65% of species) particularly in Victoria, South Australia and New South Wales. Habitat modification, including land clearing, habitat loss and fragmentation, has a similar impact (64%) in both Victoria and South Australia. Grazing is also a prominent threat (63%), mostly in Victoria, South Australia and Western Australia. Tourism and recreation is a threat for 47% of species, mostly in Victoria, South Australia, New South Wales and Western Australia. Illegal collection is also important (46%), particularly in Queensland, New South Wales and Victoria. Less common, but still important, threats for some orchids are roads and road maintenance (31%), residential and industrial development (22%), small population size and stochastic fire and weather events (19%) (Fig. 6).

Threats tended to co-occur, with the majority of orchids at risk from more than one threat and an average of six threats per species. There were only seven species listed with just a single threat including *Bulbophyllum gracillimum, Bulbophyllum longiflorum, Cepobaculum carronii*, *Corybas montanus* and *Phalaenopsis rosenstromii,* which were all threatened only by illegal collecting, while *Genoplesium rhyoliticum* was only threatened by grazing and *Prasophyllum colemaniae* was only threatened by habitat modification. Several threats co-occurred as potential threat syndromes and some clusters of threats were associated with specific habitats (Fig. 7). Clusters of threats included: (1) grazing and the presence of weeds (78% similarity), (2) change in fire regimes and habitat modification (74% similarity), and (3) tourism and recreation with grazing, weeds, change in fire regimes and habitat modification (64% similarity). Other clusters included (4) orchids in temperate forests often being threatened by tourism and recreation, grazing, weeds, change in fire regimes and habitat modification (62% similarity) while, (5) illegal collection commonly co-occurred in temperate forest habitats, tourism and recreation, grazing, weeds, change in fire regimes and habitat modification (55% similarity) (Fig. 7). In contrast to these clusters of co-occurring threats and habitats, there were others where there were no clear associations. Although climate change is listed as threatening 21 species of orchids, for example, it was not closely associated with other threats or specific habitats. Similarly, the 25 orchids growing in Mediterranean shrub vegetation were not associated with specific combinations of threats (Fig. 7).

3.4. What is the distribution of threats?

There were differences in the spatial distribution of the most common threats to orchids in Australia including change in fire regimes, weeds, grazing, habitat modification and tourism and recreation (Fig. 8). Changes in fire regimes, for example, has a greater impact in south west Australia and Tasmania than other threats (Fig. 8). The presence of introduced species, such as weeds, is spread more along the east coast of Australia in New South Wales and Queensland, where grazing is reduced (Fig. 8). Habitat modification, which includes land clearing and fragmentation, is very important on the island of Tasmania. Tourism and recreation appears to be more important in the south east of Australia in Victoria, and in south western Australia (Fig. 8). Illegal collecting is more common in the east coast of Australia including far north Queensland and New South Wales, but less so further south east in Victoria (Fig. 8).

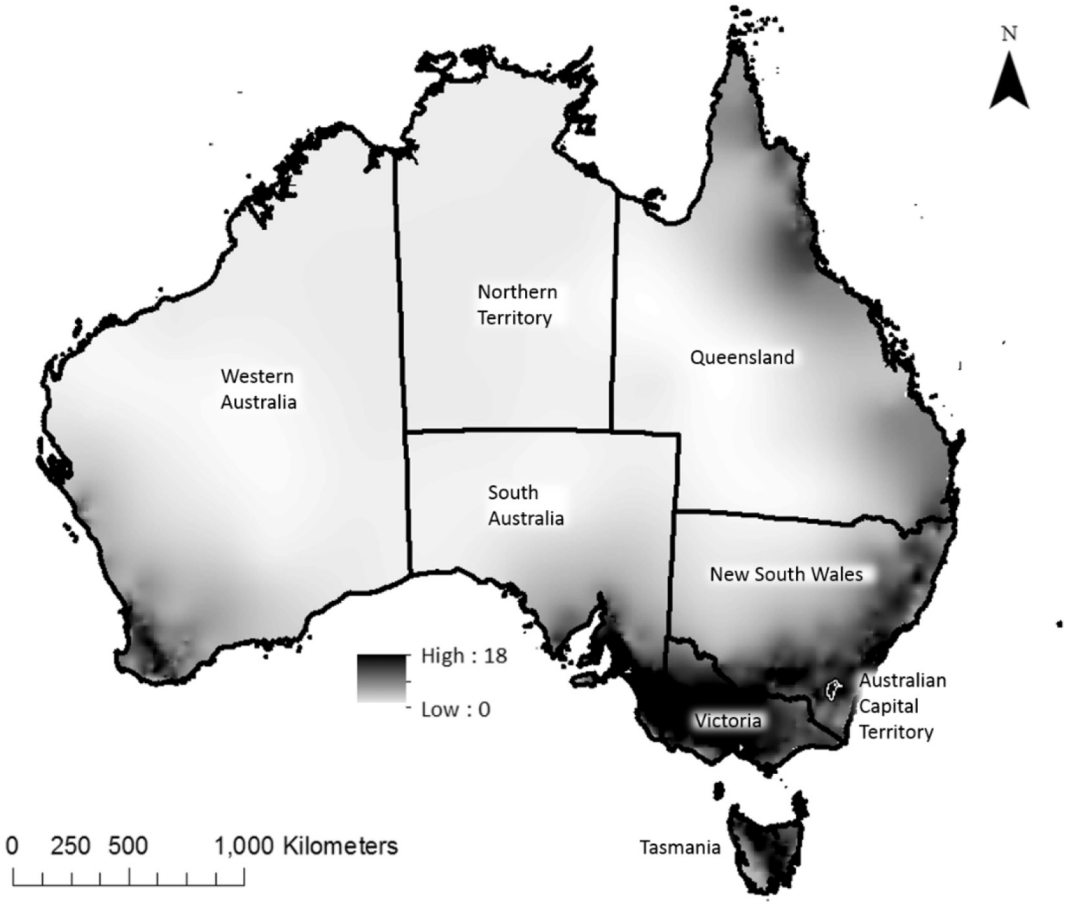

Fig. 5. The distribution of 179 threatened orchids in Australia with adequate location records in the Atlas of Australia, displayed as a spline with three standard deviations, where the lightest colour scale represents no threatened orchids present and the darkest colour represents the highest incidence of threatened orchids. The Australian Capital Territory is outlined in white.

3.5. What factors may account for the geographical patterns found in threatened orchids and in threats to orchids?

Interesting patterns are apparent in the analyses of potential factors associated with where and what threaten orchids. First, there is a moderate positive correlation ($R^2 = 0.66$) between the number of orchids and the number of threatened orchids per bioregion as would be expected (Fig. 9). Therefore, when testing if other factors were associated with common threats using Generalised Linear Models, the 'dependent' variable was the proportion of all orchids in a bioregion that were threatened rather than the absolute number of threatened orchids.

Of the four variables tested (% native vegetation cover, % protected area, % built area and Koppen climate (temperate or arid)), the percentage of a bioregion still with native vegetation was the best predictor of the risk of orchid extinction (Table 3). Bioregions with less remaining native vegetation were likely to have a higher proportion of orchids at risk of extinction, including orchids threatened by habitat modification, grazing or weeds. The proportion of the bioregion allocated to protected areas was also important, but its effect depended on the type of threats to orchids. It was associated with habitat modification, with the higher the proportion of a bioregion in protected areas, the lower the proportion of orchids in that bioregion threatened by habitat modification ($p < 0.05$). It was also a significant predictor of the proportion of orchids threatened by tourism and recreation, but there was a negative correlation so that as protected area increases in a bioregion, more orchids are affected ($p < 0.05$). It was also a predictor of the proportion of orchids threatened by changes in fire regimes with the threat of fire increasing with higher proportions of bioregions in protected areas ($p < 0.05$) (Table 3). Koppen climatic zones (temperate or arid) and the percentage of built areas were not significant predictors of overall threatened species or individual threats ($p > 0.05$).

4. Discussion

4.1. How many threatened orchids are there in Australia?

Orchids are the most threatened group of flowering plants globally, with a similar suites of threats (Wraith and Pickering, 2017, 2018), and Australia is no exception, with 184 species listed as threatened by the Australian Government (Backhouse, 2007; Swarts and Dixon, 2009a; Australian Government, 2016b). Threatened orchids in Australia are mostly terrestrial species in the Orchidoideae subfamily and are commonly listed as endangered, which is perhaps linked with their niche habitat requirements and specific species associations with mycorrhiza and pollinators (Whigham and Willems, 2003; Swarts and Dixon, 2009a; Nevill, 2010). Similar to orchids across the globe, threatened terrestrial orchids in Australian tend to occur in temperate forest and shrubby habitats, which are often areas under immediate risk of anthropogenic threats such as large-scale changes in land use (Millar and Stephenson, 2015). For example, in Australia, the state of Victoria is home to the highest number of threatened orchids, especially those in habitats dominated by plant communities that are themselves threatened, such as the Western Basalt Plains Grassland in the Southern Volcanic Plains bioregion in Victoria (Duncan et al., 2005). This habitat has been reduced to 1% of its original size, yet the bioregion has among the highest numbers of threatened orchids in Australia (22 species).

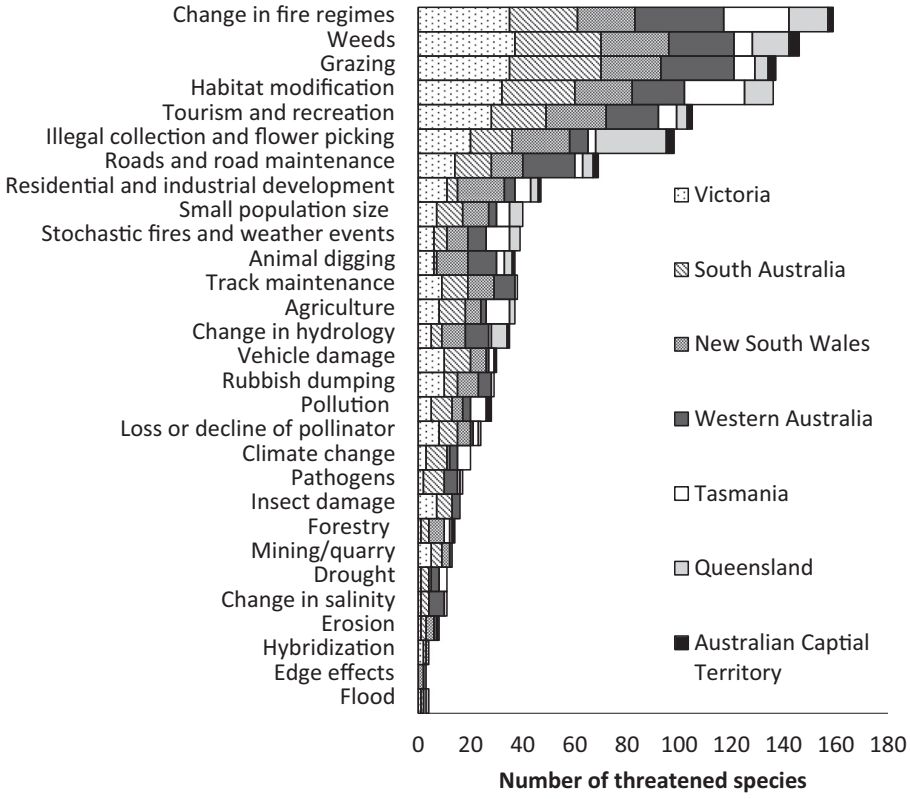

Fig. 6. The number of orchid species listed as threatened in each state and territory by threat type.

Epiphytic orchids in Australia, are more often listed as critically endangered than terrestrial species and often fall within the Epidendroideae subfamily. This reflects global studies which show terrestrial species are listed as threatened more frequently, but epiphytic species are at a higher risk from overexploitation (Swarts and Dixon, 2009a).

4.2. What threatens orchids in Australia and where?

There were six major threats to orchids in Australia: changing or inappropriate fire regimes, habitat modification including land clearing and fragmentation, grazing, invasive species such as weeds, tourism and recreation and illegal collection. These threats are similar to those found for orchids globally, particularly European Red Listed species, however, Australian species are more commonly impacted by fire and land clearing (Bilz et al., 2011; Brummitt et al., 2015; Reiter et al., 2016; Wraith and Pickering, 2017, 2018; Fay, 2018). Threats to orchids in Australia often co-occurred and hence can be treated as threat syndromes. For example, species threated by habitat modification were often also threatened by weeds, grazing and fire. Hence these four threats will often need to be managed together to reduce the risk of

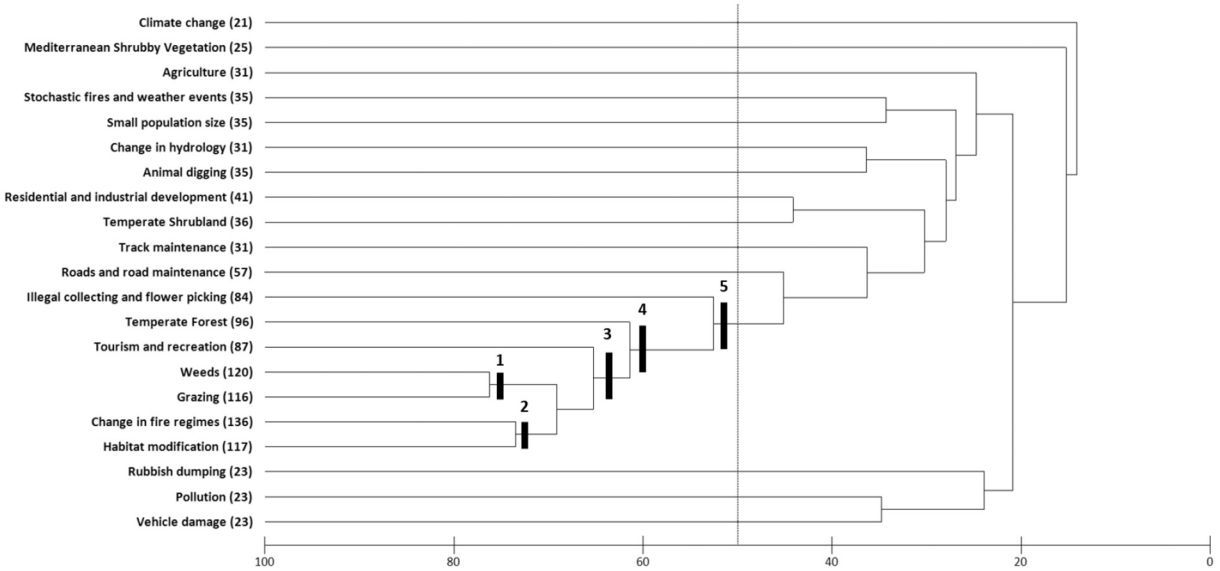

Fig. 7. Bray Curtis cluster analysis showing the levels of similarity (percent) among threats and habitat types for threatened orchids in Australia, with threat syndromes and habitats (clusters) highlighted in black and labelled 1–5 and number of species in parenthesis.

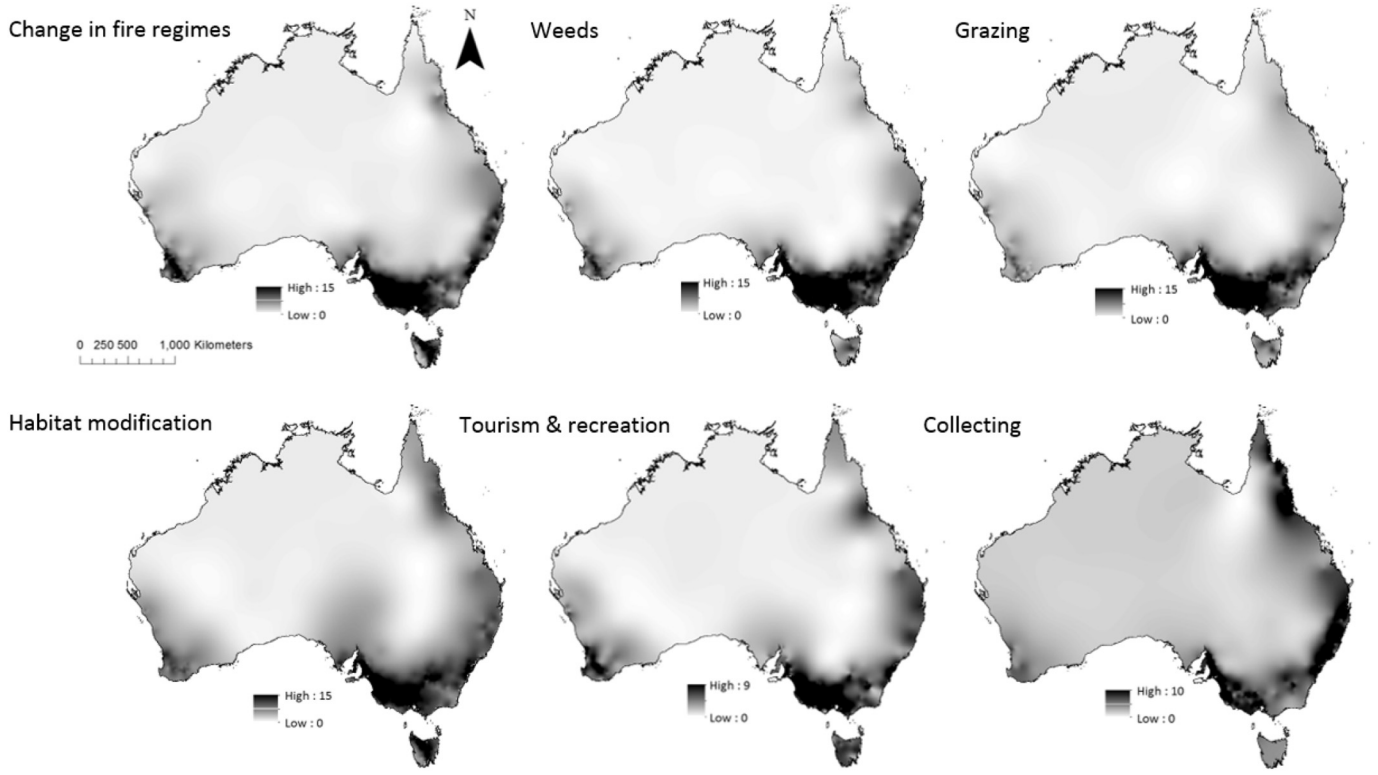

Fig. 8. The distribution of the six most common threats to threatened orchids in Australia displayed as a spline with three standard deviations, where the lightest colour scale represents no presence of threatening process and darkest colour represents highest incidence of the threatening process for the 179 species with adequate data in Atlas of Australia.

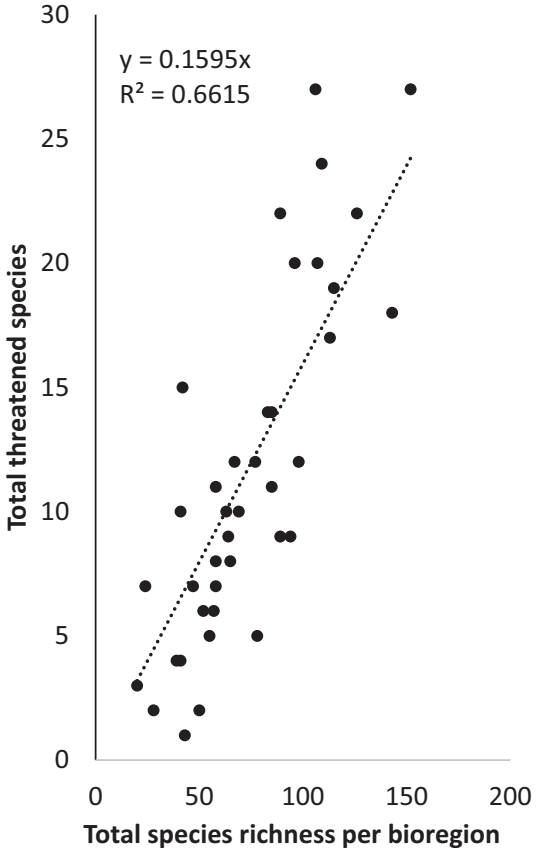

Fig. 9. Relationship between the total species richness and the total number of threatened species per bioregion, using all bioregions with 20 or more species.

extinction to orchids in specific locations by limiting further land clearing, protecting remnant vegetation, better fire management and in some cases, using fences to limit grazing by domestic livestock (Nevill, 2010; Waudby et al., 2018). This syndrome of threats is similar to that found for all plants across Australia in another study that used threatened species lists (Burgman et al., 2007). A key difference for orchids, however, is that tourism and recreation and illegal collecting are also important threats.

There are geographical hotpots of threatened orchids in Australia. These hotpots are partly explained by the overall diversity of orchids in bioregions, but also by the concentrations of threats. By mapping the distribution of threats across the continent, we have highlighted areas where orchids are at increased risk of one or more major threats and therefore areas where, without effective action, many orchids will be lost. For example, Victoria in south eastern Australia is a hotspot for every major threat to orchids, including habitat modification, weeds and grazing. Unsurprisingly, these threats are associated with the general loss of native vegetation cover in bioregions in Victoria. The large number and proportion of orchids threatened in Victoria reflects extensive land clearing in the past, with 60% of the state's native vegetation cleared mainly for agriculture (Duncan et al., 2005). With the removal of native vegetation, the remaining areas of native vegetation in Victoria are vulnerable to invasive weed species, particularly introduced grasses which are known to outcompete terrestrial orchids (Nevill, 2010). In contrast, where a high proportion of bioregions were in protected areas across Australia, habitat modification was less of an issue.

Although protected areas reduce the risk of habitat modification, it increases the risk from tourism and recreation to orchids, which is increasingly recognised as a major threat to orchids globally (Wraith and Pickering, 2017) including in Europe (Bilz et al., 2011; Ballantyne and Pickering, 2013). Interestingly, orchids in protected areas are at a higher risk of the negative impacts from tourism and recreation

Table 3
Significant predictor variables for the percent of threatened species and threatening processes within each bioregion using a quasi-Poisson generalised linear model with a log link distribution (P value = the probability value and correlation = positive or negative relationship between variables).

Dependent variable	Independent variable	*P* value (< 0.05)	Standard error	Correlation
% threatened species	% native vegetation cover	0.0307	0.0042	Negative
% species threatened by habitat modification	% native vegetation cover	0.0394	0.0031	Negative
	% protected area cover	0.0414	0.0034	Positive
% species threatened by grazing	% native vegetation cover	0.0186	0.0053	Negative
% species threatened by weeds	% native vegetation cover	0.0435	0.0055	Negative
% species threatened by tourism	% protected area cover	0.0076	0.0049	Negative
% species threatened by fire	% protected area cover	0.0415	0.0030	Negative

including impacts associated with the construction and use of facilities for transport (roads, trails) and accommodation (hotels, cabins, campsites), as well as specific activities, such as trampling from visitors either by foot, vehicles, bikes and horses (Liddle, 1997; Kelly et al., 2003; Pickering et al., 2007; Nevill, 2010; Holden, 2016). In some protected areas large numbers of orchid enthusiasts not only increase the risk of trampling to terrestrial orchids when photographing them, some also can increase the risk of illegal collecting (Ballantyne and Pickering, 2012; Wraith and Pickering, 2017). Illegal collecting is a prominent and important threat to orchids on a global scale, for example the highly prized and charismatic genera *Paphiopedilum* and *Cypripedium* which account for 28% of orchids on the IUCN Red List are most commonly impacted by illegal collecting (IUCN, 2016a; Wraith and Pickering, 2017; Fay, 2018; Li et al., 2018).

The tropical north eastern Australian in Queensland was a hotspot for illegal collecting, particularly of epiphytic species which are often targeted due to their ability to do well in cultivation and are often used in propagation (Seaton et al., 2013). Mitigating the impacts from tourism and recreation and illegal collecting is important for the conservation of orchids, particularly those that are highly prized for their beauty and rarity (Ballantyne and Pickering, 2012; Wraith and Pickering, 2017). Strategies to minimise these impacts include educating tourists and members of orchid societies about their impacts on orchids, creating physical boundaries around high risk areas to reduce the effects of trampling, and enforcing strict regulations on collecting wild plants (Swarts and Dixon, 2009b; Waudby et al., 2018).

Similar to tourism and recreation, the threat of fire was greater when more of the bioregion was conserved in protected areas (Table 3). Changing fire regimes poses a significant risk for orchids globally, with fire ranked as the 12th most common threat to orchids in Europe with similar impacts in North and South America (Bilz et al., 2011). However, the threat appears to be even more severe in Australia as changing fire regimes is the most commonly listed threat, particularly in temperate areas of south western Australia and in Tasmania (Swarts and Dixon, 2009a; Bradstock, 2010). Western Australia has numerous threatened orchids (35 species), particularly in the southern region of the state within the Jarrah Forest bioregion (20 species). This area consists of Mediterranean type shrubby habitat and comprises a large portion of the Southwest Australia Floristic Region which is a known hotpot for terrestrial orchid diversity (374 species) but is subjected to frequent planned and unplanned burns (Hopper and Gioia, 2004; Bonnardeaux et al., 2007; Burrows, 2008). Many terrestrial orchids can cope with natural fire cycles in Australia, in part as they have dormant underground tubers, however, frequent fires during the flowering season can be detrimental, particularly for species with small population sizes (Nevill, 2010; Jasinge et al., 2018). Prescribed burning during the dormant stage for terrestrial orchids is therefore preferable and has been successfully implemented into certain management plans in Victoria (Jasinge et al., 2018). However, more research on the effects of fire on specific terrestrial orchids, including the effects of prescribed burns on orchids within national parks is important to reduce population declines (Jasinge et al., 2018).

4.3. Climate change an underrepresented threat

Although climate change was only listed as a threat for 21 species by the Australian Government, this does not reflect current understanding, with recent studies highlighting that many orchids in Australia are threatened by climate change (Reiter et al., 2016; Simmons et al., 2018; Simpson et al., 2018). Orchids are particularly at risk from climate change because of their narrow geographical ranges and specific symbiotic associations with fungi and pollinators which are also affected by climate change (Fay, 2018). Climate change will further limit suitable habitats for many orchids in Australia, as well as enhancing existing threats such as fires, the spread of weeds and increasing the impact of dry conditions in general. For example, the risk of fires and drought is already increasing in Australia due to climate change, and both are important threats in their own right to many populations of orchids (Nevill, 2010; Seaton et al., 2013).

Other ways in which climate change is directly and indirectly affecting orchids is seen in the endangered Australian subterranean orchid, *Rhizanthella gardneri* in Western Australia. Increasingly dry hot conditions, along with phenological shifts in flowering due to climate change is already causing a disconnect between this orchid and its symbionts in Western Australia (Swarts and Dixon, 2009a; Liu et al., 2010; Seaton et al., 2010). Similarly, the terrestrial species *Phaius australis,* which is listed as endangered in eastern Australia, is only found in coastal habitats that are changing due to warming and drying conditions in the region (Simmons et al., 2018), but climate change is not currently listed as a threat. Many epiphytic orchids are also at risk of climate change due to their reliance on specific habitats, including cloud forests which are declining rapidly with the warming climate (Foster, 2001; Brodie et al., 2012; Ponce-Reyes et al., 2012; Seaton et al., 2013). For example, in the Wet Tropics World Heritage Area in north Queensland, climate change is predicted to result in major changes in plant communities including the potential loss of the cloud forest, which will adversely affect epiphytic orchids in the region (Costion et al., 2015).

The underrepresentation of climate change in threatened lists is also seen at a global level. For example, of the 442 orchids with detailed threat data on the IUCN Red List, climate change is only listed as a threat for 85 species (19%) (IUCN, 2016a; Wraith and Pickering, 2017). However, climate change has already resulted in the loss of orchids in many regions (Liu et al., 2010; Seaton et al., 2010; Vogt-Schilb et al., 2015). This includes in Central America, where increased temperatures and altering fire regimes in the mountain rainforest in the Montebello region of Mexico caused 22 endemic orchids to go extinct and changes in precipitation has caused severe declines in Panama (Zotz and Schmidt, 2006; Seaton et al., 2010). Populations of European orchids have also declined, and range shifts occurred due to climate change, with terrestrial species increasingly limited to northern latitudes (Pfeifer et al., 2010; Molnár et al., 2012; Vogt-Schilb et al., 2015). It is clear that orchids are threatened by climate change, but more detailed research is required to better understand which species, where and why climate change is affecting orchids. Also, conservation listings need to be updated to better represent this increasingly important threat to

orchids and other biota (Nevill, 2010; Seaton et al., 2013).

4.4. Limitations to threatened species listings

This study has highlighted patterns in threatening processes across the continent of Australia, however, there are important limitations to be kept in mind. Firstly, lists of threatened species and their threats, do not always fully reflect reality. This includes clear examples such as the Australian Government lists not reflecting impacts of climate change already occurring in Australia. Threatened orchids are found in many states and territories in Australia and in many regions internationally but the process for listing orchids varies among jurisdictions. For example, there are 42 orchids listed by the Australian Government as threatened in Victoria, but there are 370 listed by the Victorian Government as threatened (Duncan et al., 2005). Part of this discrepancy is that the 370 will include species doing well outside Victoria but poorly within the state. Also, there are 184 orchid species listed as threatened by the Australian Government but are only five species of orchids listed internationally on the IUCN Red List as threatened within Australia (Wraith and Pickering, 2017). The underrepresentation of Australian orchids in the IUCN list highlights the importance of ensuring this global list is accurate including for prioritising conservation efforts at a global scale (Gärdenfors, 2001; Rodrigues et al., 2006). Differences among lists are due to a range of factors including delays in listing and delays in updating threats for species already listed, as well as differences in the ways threats are categorised (Rondinini et al., 2014). These issues are occurring across the globe (Schatz, 2009) and conservation efforts will benefit by adopting consistent approaches to global species listings, particularly on databases such as the IUCN Red List (Hoffmann et al., 2008; Brito et al., 2010).

A second limitation of the current study is that the distribution of orchids and threats was mapped using data from the Atlas of Living Australia. Although this is an important and useful source of occurrence records for species across the continent, it should be treated with caution. The location data used here, was screened extensively for inaccuracies, but there remain a range of errors with such records (Graham et al., 2008; Feeley and Silman, 2010). The distributions of the orchid species in the database will be affected by survey bias with an underrepresentation of orchid locations in remote areas. There is also the issue that in many cases data points are left vague including coordinates with only one decimal point. This is often done deliberately for rare species to avoid illegal collection and an influx of enthusiasts to the location. Also, the distribution of an orchid in a specific location does not mean it is threatened there by all listed threats in that location. Therefore, using location data as a surrogate for threat maps is likely to over-estimate the distribution of some threats and underestimate them in areas with less sampling effort.

More accurate occurrence data and threat mapping will obviously improve the current results, although accurate location data will remain sensitive due to the risks to rare species, particularly orchids targeted by collectors. Secondly, this is a broad scale analysis which is useful when looking at a continental level, but further research is required to highlight patterns at a finer scale. This should include ‘ground truthing’ data using field surveys and other sources of data, particularly in remote areas to deal with current deficiencies is location data.

5. Conclusions

This study demonstrated the need to conserve key habitats and mitigate a range of threats, so orchids can survive changing environments due to a diversity of anthropogenic activities. To achieve this, attention needs to not only focus on the threatened species and single threats but also incorporate threat syndromes and whole ecosystems. For orchids in Australia, key threats which often co-occurred include habitat modification, changing fire regimes, grazing, weeds, tourism and recreation and illegal collection with the loss of habitat critically important. Even where orchids are protected from many changes in land use within protected areas, tourism and recreation is still an issue and needs to be better addressed. The results also highlight that climate change is underrepresented as a threat to orchids, despite the spread and scale with which it is already affecting species globally and in Australia. The results also highlight the importance of updated listings of species to better reflect reality, and the need for further research into threats to orchids, and ways to ameliorate them before even more orchids are lost.

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